THE DETERMINATION OF STATIC AND TIME VARYING DIPOLE SOURCE — SENSOR GEOMETRY DURING SEA TRIALS USING DIFFERENTIAL GLOBAL POSITIONING SYSTEM

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The Determination of Static and Time Varying Dipole Source – Sensor Geometry During Sea Trials Using Differential Global Positioning System

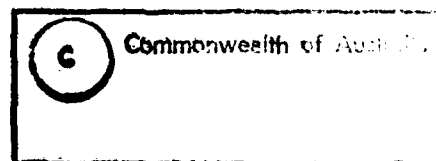## J. Vrbancich, A. Donohoo, L. Scott, S. Turnbull and M. Andreaus

Abstract

Global positioning system (GPS) navigational equipment is used in differential mode to determine the time varying geometry of a boat attached to a submerged dipole source and a sensor positioned on the seafloor which is marked by a surface buoy. The requirement is to track the position of the source relative to the sensor on the seabed in sea depths less than 40 metres in the vicinity of Sydney Harbour. A differential GPS (DGPS) system is formed from two or three low cost navigational units, one of which is located at a surveyed reference site and the other is located onboard the vessel. A third unit may be temporarily located at the sea surface above the sensor positioned on the seafloor. The differential system relies on software developed to apply the GPS correction obtained from the reference station to the remote stations after the geographical coordinates have been recorded. Static DGPS measurements using a 7 km baseline between remote and reference datums gave a position accuracy limited by the resolution of the GPS receiver. As a test for kinematic DGPS, the positional accuracy of the moving vessel was checked against the position coordinates derived from the laser tracking facility of the Shark Point Degaussing Range, Sydney Harbour. The agreement was usually found to be better than about 5 m, typically ± 2 m. DGPS also enabled accurate submarine tracking at periscope depth by interfacing the submarine UHF antenna to the GPS receiver. A discussion of operational issues in the use of DGPS is also included.

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The Determination of Static and Time Varying Dipole Source – Sensor Geometry During Sea Trials Using Differential Global Positioning System

1. Introduction

The time varying geometry between a submerged dipole source and sensors positioned on the seafloor is required for a better understanding of the propagation of signals in sea water. The dipole source can either be an artificial source attached to a vessel, and excited by a known current and frequency, or it can represent a ship source. The position of the seafloor sensors are indicated by a surface buoy. This report discusses the methodology, based on the application of the global positioning system, GPS, to accurately determine the position of the dipole source relative to the surface buoy marking the seafloor sensors, during sea trial conditions. A discussion of the problems associated with using GPS to obtain a position fix on a seafloor datum, by GPS tracking the surface buoy marking the datum, is also included.

Following a brief overview of GPS, the problem of obtaining relative distances between geographically fixed datums is presented as this case represents a simplification of the problem. Here, neither positions are moving and the accuracy of the relative positions using GPS can be checked because each datum was originally known from conventional surveying techniques. The methodology for determining time varying relative positions during sea trials is then presented and the accuracy of the technique is compared to independent laser tracking methods.

1.1 An Overview of GPS

GPS is a global positioning system, developed by the US Department of Defense, to enable the quick and accurate determination of location anywhere in the world [1,2]. Relatively inexpensive GPS receiver systems can give results accurate to 100 metres or better and can be used for both static and kinematic position fixing.

The system is based on a constellation of 21 non-geostationary satellites with a 12 hour orbit at an altitude of about 20183 km. Each satellite continually transmits two carrier frequencies of 1575.42 MHz and 1227.6 MHz which are modulated by a 50 Hz message and two unique binary pseudo-random noise (PRN) codes: the Coarse Acquisition (C/A) code (1.023 MHz) and the Precise (P) code (10.23 MHz). Timing accuracy is provided by the satellite's atomic clocks which are synchronized with those of other satellites to provide a universal GPS time.

'Pseudo ranging' is the simplest mode of operation. Here, GPS triangulates the position of a receiver by measuring its range to either three or four visible satellites by correlating the C/A signal arriving from a given satellite with a delayed receiver generated replica. Ideally, the delay required to match the two signals is equal to the signal arrival time, or satellite range, but because the receiver is controlled by its own clock, imperfect synchronization with the satellite clock rate introduces error. To overcome this indeterminacy, ranging to an additional satellite is performed, i.e. 3 satellites are required for a 2D solution, a full 3D solution (position and altitude) requires 4 satellites to be tracked. Once the pseudo ranges have been performed, the receiver position is calculated from the satellite ephemerides[1]. The pseudo ranging method is described in Figure 1.

Poor relative satellite geometry introduces an additional inherent error known as the Dilution of Precision (DOP) factor, which increases if the satellites are not well separated across the sky, see Figure 2. With a measurement accuracy of 10 metres, a DOP factor of 3 indicates a position uncertainty of 30 metres. A DOP close to unity is desirable, but is not always possible. The DOP factor changes with time because satellites being tracked do not remain in fixed positions. The Horizontal Dilution of Precision (HDOP) is specified in this report since altitude is a known parameter and consequently, only 2D GPS solutions are required.

Deliberate degradation of the C/A signal, known as 'Selective Availability' (SA), is unpredictably imposed by the US Department of Defense for security reasons, because unlike the P code, availability of the C/A code is unrestricted. SA decreases the accuracy by a factor of three. With contributions from all of the above sources, an overall error of about 100 metres can be expected.

The effects from most of the above errors can be eliminated by employing a technique known as relative or differential GPS (DGPS). Pseudo ranging measurements are made using the C/A code and an additional receiver unit is operated simultaneously at a distant reference station. If the reference site has been previously surveyed so that its position is precisely known then the instantaneous error given by the GPS in that location is easily determined. Given that the reference receiver is tracking the same satellites, and that it has the same specifications of the remote GPS receiver, its error is virtually identical. Accuracy can be increased to better than 5 m by applying the reference station corrections to the remote receiver. Usually the separation of receivers over which differential corrections are valid extends to a hundred kilometres or more. Over very large distances, the receivers might not track a particular combination of satellites at exactly the same time, but if there is sufficient overlap the differential correction can be applied for that duration.

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[1] Ephemeris data refers to the predictions of current satellite position that are transmitted to the user in the data message. Satellite range measurement inaccuracy may also result from small ephemeris errors as well as ionospheric and atmospheric delays which cannot be accounted for using the pseudo ranging method.
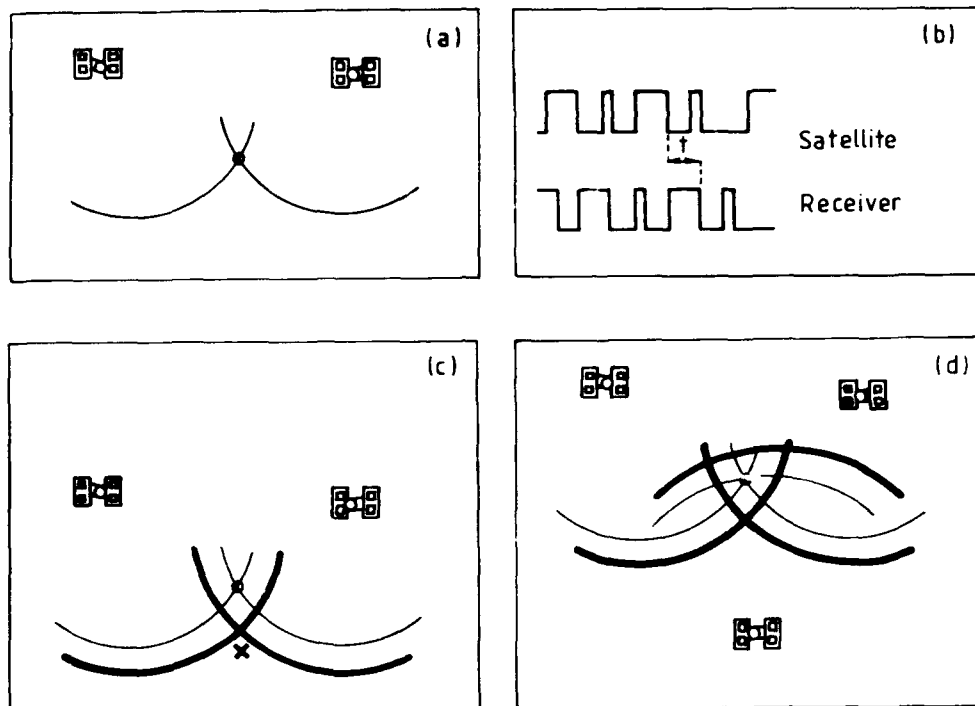
Figure 1: *2D pseudo range position fixing. (a) the exact position can be determined by ranging from each satellite; (b) the range is determined from the signal arrival time represented by the time lag between the signal arriving from the satellite and a receiver generated replica; (c) the pseudo range measurement gives an incorrect position fix at X if there is a timing error in the receiver; (d) by ranging an additional satellite, the ambiguity in (c) is removed because the timing error is computed by the receiver to give a single point of intersection.*
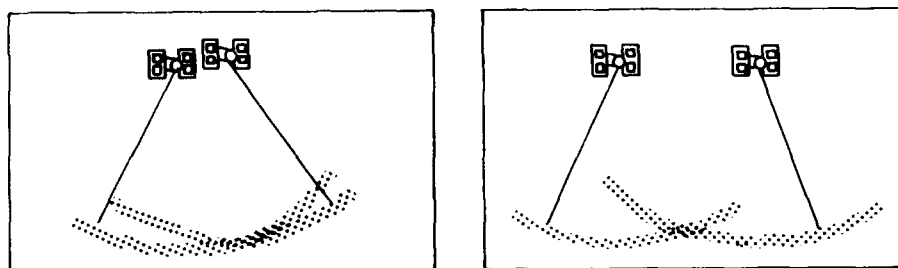

Figure 2: *Effect of relative satellite geometry: the Dilution of Precision factor. Pseudo ranges represent "fuzzy" measurements owing to errors arising from clock bias, ionospheric delays and ephemeris information. The overlapping area and subsequent pseudo ranging error is reduced by a more favourable satellite geometry with a larger inter-satellite separation.*

True DGPS systems are able to apply corrections in real time using radio or telephone communication to transfer data from the reference station receiver. In addition, the data required to apply the differential correction is transmitted to the remote station in a form individualised for each satellite, rather than an overall geographical (latitude/longitude) coordinate correction Real time solutions may not be necessary however. By interfacing each receiver with a computer and storing its position and time data, the information may be processed later, see Figure 3. This method is much less expensive and enables evaluation of the raw data if required. Close agreement between results obtained from simultaneous applications of DGPS and laser tracking at the Shark Point Degaussing Range has confirmed the versatility of DGPS for recording the accurate position of a moving vessel at two second intervals under the usual sea trials operating conditions.

Owing to world-wide coverage, GPS is not restricted to specific locations. With a permanent reference station at Pyrmont, DGPS can be used for a mobile receiver anywhere in the Sydney region provided satellite conditions are favourable. The laser tracking system is more accurate than the DGPS system however its application requires additional personnel and it cannot be used during periods of rainfall. DGPS is also useful for static site surveys where the geographical coordinates of a fixed above-water or underwater sensor must be determined. In the latter case, sensor position accuracy is degraded by the means used to mark, on the sea surface, the location of the sensor datum on the seafloor, see Section 4.2. Sea trials have involved the use of kinematic DGPS for obtaining accurate tracks of vessels and static DGPS for obtaining sensor positions either on the seafloor, marked by a surface buoy, or above the sea surface.

2. *Equipment*[2]

The primary component of the GPS instrumentation is the hardware used to track the satellites. The receiver consists of an antenna and preamplifier along with a unit which contains a radiofrequency stage, microprocessor control and a display. The unit can be powered by a battery or any suitable DC power supply. A computer is used for recording the data so that differential corrections can be made at a later time. The FURUNO GP-500, costing approximately $3000, is used in these experiments. It has two channel satellite tracking and multiplex tracking for up to five satellites, using the C/A code. The GPS receiver provides a choice of 170 geodetic coordinates, apart from the world geographical system WGS84/72, applicable to the local area of interest. In these experiments, the Australian geodetic datum coordinate system (AGD) was chosen, see Appendix. An important feature is the ability of the receiver unit to provide geographical coordinates with minutes evaluated to three decimal places, giving a precision of 1.8 m.

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[2] The use of commercial GPS receivers and satellite prediction software (Section 3.1) does not represent an endorsement by DSTO in favour of these products.
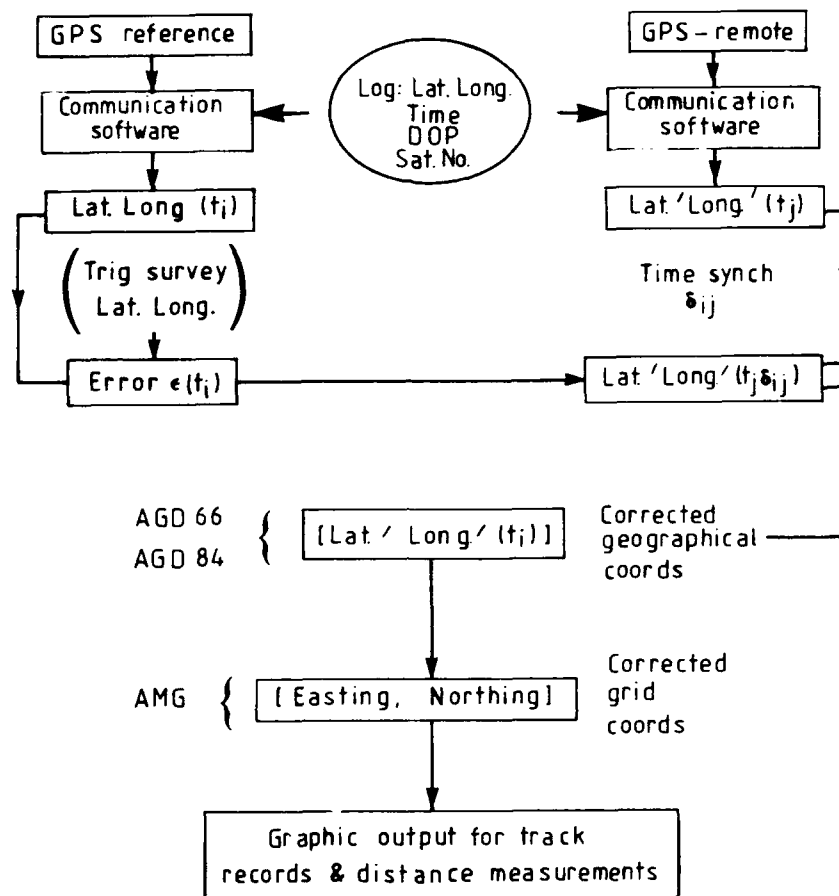
DIFFERENTIAL GPS

2 - 5 m accuracy

Figure 3: Post-processing of GPS data to obtain the differential correction and relative distances. "PROCOMM" software is used to log geographical coordinates along with time, HDOP and if possible satellite number. The reference file times (t_i) and remote file times (t_j) are synchronised so that the position error at time t_i is transferred to the remote position coordinates which are expressed in either AGD66 or AGD84 coordinates. A separate software routine then translates the differentially corrected geographical coordinates to grid coordinates (AMG) for recording tracks and distances.

The GPS antenna includes a preamplifier with sufficient gain to enable the signal to overcome cable attenuation prior to processing by the GPS receiver. Owing to the gigahertz transmission frequency, an antenna location requiring longer than the standard 15 m cable length will result in excessive signal losses. The Pyrmont reference station uses an antenna mounted on top of a seven storey building at a height of 36 m above sea level. Low attenuation cable (type 10DFB) enables the receiver to be placed up to 100 m from the antenna. A 40 m length of more flexible

higher attenuation rate cable (RG-213/U) connected to the supplied GPS aerial was used in the submarine, see Section 5.2.2, when the UHF mast with its own cable link was not available.

A serial interface to a laptop computer enables the logging of appropriate GPS data. The GPS unit must have the provision for logging time, geographical coordinates and satellite status. In the case of the FURUNO receiver, only DOP factors can be logged whereas ideally, actual satellite identification numbers used to determine the position at a given time need to be logged in order to obtain fidelity when applying the differential correction to the remote receiver. Data from an 8 hour recording of the unattended reference station can be easily stored on a single high density diskette. A schematic diagram of the GPS system is shown in Figure 4.
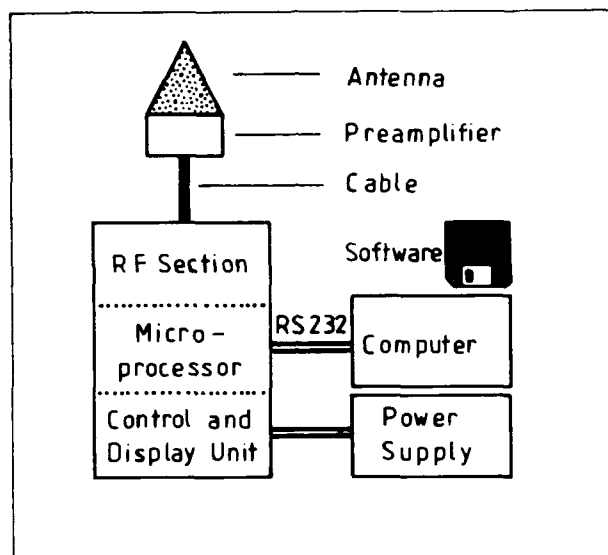
Figure 4: Components of the remote and reference GPS system.

3. Software

3.1 Satellite Prediction

The second component of the user system consists of supporting software. This ranges from commercially available satellite prediction programs, to user specific programs for processing the position data.

An important element of the software support is a satellite geometry and visibility prediction utility which is needed in order to determine the likelihood of a high DOP or otherwise unsuitable conditions for maintaining reliable fixes. Obviously reliable boat tracking cannot be performed successfully in the case of bad satellite geometry or rapidly changing satellite combinations since there is a

probability of occasional mistracking. With some foreknowledge of satellite conditions, optimum periods for GPS use can be chosen. Generally, four or five satellites are within view at any location and time.

"Satviz" software from Trimble Navigation has been used to predict satellite conditions, but other software is available. The main features of this program are graphic displays indicating the satellites available for tracking, satellite selection ensuring minimum DOP, viewing periods of the satellites and elevation and azimuth polar plots for visible satellites. This information is determined from an almanac file or downloaded almanac, on the basis of user entered parameters called a 'scenario' which includes observer geographical coordinates and observation date/time/duration. For a specific scenario, the satellites which will be tracked over the selected time can be displayed. Once this is known, their positions and movement in the sky can be viewed to determine whether possible obstructions from the environment might occur. If, for example, a tall building blocks the signal path of a satellite, it is possible to incorporate a mask angle in the scenario so that satellites low in the sky can be igno. ed. The DOP can then be evaluated using the remaining satellites. If a satellite is found to be in an unsuitable position and another satellite choice is available, the unsuitable satellite can be manually overridden on the GPS receiver. The resulting DOP may not necessarily be any worse because it is possible to have different satellite combinations with similar or identical DOP characteristics.

Satellite information must be up to date for reliable predictions. Current almanac files are purchased or downloaded from a suitable GPS receiver.

3.2 Differential GPS

Communications software (for example PROCOMM) is required for recording the GPS data arriving through the serial port from the receiver's RS232C interface. The rate of acquisition can be selected. Data output from the FURUNO GP-500 follows the National Marine Electronics Association's (NMEA) Standard for interfacing marine electronics navigational devices. In general this is simply information for navigation and includes little information on satellites or GPS conditions apart from that given in the format used in these experiments, where a computer records 62 byte ASCII strings at two second intervals. Each string, identified by the "GGA" format identifier within NMEA, includes the time, latitude, longitude, altitude, HDOP, total number of satellites being tracked and tracking success or failure. It is not possible to record some of the information displayed on the receiver panel, in particular the identification number of a satellite being tracked. This makes it difficult to assess if the same satellites are being tracked by two receivers in a differential system, which is necessary if extraneous positions emerge after differential correction.

The recorded data is processed using software developed at MOD, Sydney. Each program performs relatively simple tasks, see Figure 3. The conversion of geographical coordinates to grid coordinates (AMG, ISG see Appendix) is based on reference [3]. The first stage extracts the time, latitude, longitude, HDOP and satellite tracking status from the reference station and remote station data files once the two data files have been synchronised in time. A reference station file is much longer than a boat track file because data from the former is logged without interruption over many hours while a boat track generally lasts only a few minutes. Reference station position data is compared to its correct latitude and

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longitude and the time varying offset is subtracted from the latitude and longitude of the corresponding 'kinematic GPS' data file. The result is the desired differential correction. Other output contains the raw position fixes of the mobile receiver and HDOP values from both GPS receivers. Inspection of the HDOP file gives some indication of the validity of the differential technique; differing HDOP factors suggest that conditions at both receivers were not identical.

At this stage, all position information remains in a geographical datum. For evaluation of source-sensor geometry, conversion to an Australian Mapping Grid (AMG) datum is carried out on the corrected data providing easting and northing coordinates in metres. Each line of the completed track file contains a time reading, with corrected latitude, longitude, easting and northing positions. An additional program is used to graphically display the information as a 'track' on a map so that distances from a fixed coordinate can be directly measured .

Procedures are identical for a static GPS survey. A 'track' from a stationary antenna will show a localized spread of discrete points, owing to the resolution of the GPS receiver which in this case is slightly less than 2 metres. Not all points in the spread have an equal probability of recurrence, so a simple weighting is performed to determine the most likely corrected position of the antenna. Over a short time, the error associated with this is roughly equivalent to the spread of data, usually a few metres. By averaging the corrected latitude and longitude values over many minutes, the location can be determined to within the tolerance of the receiver, see Section 4.1.

4. Static DGPS

4.1 Terrestrial Measurements

The full potential of the differential positioning system is evidenced when a static survey is performed. The differential correction technique gains its accuracy from the premise that over a local region, signals arriving at spatially separated receivers will have incurred virtually identical errors. If the exact error at one of the receivers can be calculated then this should indicate the error at the same time at the other receiver. In fact, the signals arriving at two separated receivers do not exactly correspond and this contributes to the limited accuracy of DGPS. However the variations can be further minimized by averaging the fluctuations over time, because the errors at each receiver do not remain constant. This is not possible if one of the receivers is in motion.

At any instant in time, a differentially corrected position fix may be in error by perhaps 5 m. Whilst this represents a considerable improvement over the uncorrected C/A code position fix, it may not be adequate for some applications such as a site survey. In the course of a few minutes a corrected position fix varies between clearly visible extremes. The exact position of the antenna lies somewhere close to the centre of this range. Observations using two fixed position antennas, separated by several kilometres, were recorded for the case where the antennas were situated at previously surveyed sites. This procedure enables the overall accuracy of the DGPS system for a particular receiver as well as the increase in accuracy afforded by time averaging of the data to be assessed. From

one receiver the correction to be applied at the other is recorded. After processing, the exact location of the second receiver can be compared to its GPS predicted value to determine the overall accuracy of static DGPS positioning. Furthermore, such measurements give insight into the correspondence between errors at separated receivers, especially the effect of satellite changes on the HDOP and overall error, as well as providing an estimate of the minimum duration required for an accurate static DGPS measurement.

The first survey consisted of two receivers placed at sites where the coordinates of the antenna positions were previously determined by surveying methods. The reference station for this test was DSTO Pyrmont[3] and the 'survey' site was the Blocks E datum at the RAN Hydrographic School at *HMAS Penguin*, some 7 km away. During the period of observation, a single combination of satellites was tracked by both receivers. Under these conditions there should be relatively good correspondence between position fluctuations.

Figure 5 summarises the results for a 30 minute data record taken from each station. In this case, the Pyrmont datum was used as the reference to predict the coordinates of the *HMAS Penguin* datum. The spread of values after differential correction (Fig. 5a) clearly shows the discrepancy between receivers at each point in time: the differentially corrected position data varies over a region of up to about 8 m from one extreme to the other, in both easting and northing directions. Over this period the *uncorrected* GPS data varies by up to 100 m. By taking the average position over the duration of the record, agreement to within the instrument resolution of the receiver was obtained, see Figures 5b,c. Whilst the spread of values is about 8 m, the difference between the mean and true position is far less, representing an accuracy of better than 2 m overall.

Generally, the longer the acquisition record, the greater the improvement in the static position estimate. Inspection of Figure 5 indicates however that the full spread of position values occurs in a time less than the total duration of the file. It can be reasonably expected that results with a similar overall accuracy could be achieved without recording data for this length of time. However if the sample is too short, a fair representation of the variations in position might not be observed, so that the overall error would not be reduced by averaging and the fix would be biased towards a particular direction. Depending on the satellite status at the time of recording, 10 minutes or less of data would be adequate in most cases.

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[3] The DSTO Pyrmont datum was established during this period of work to provide a permanent reference point for differential applications. Its secure location on the roof of the seven storey building with virtually no obstructions is ideally suited for this purpose. The datum represents a third order point with an accuracy of ± 40 cm.
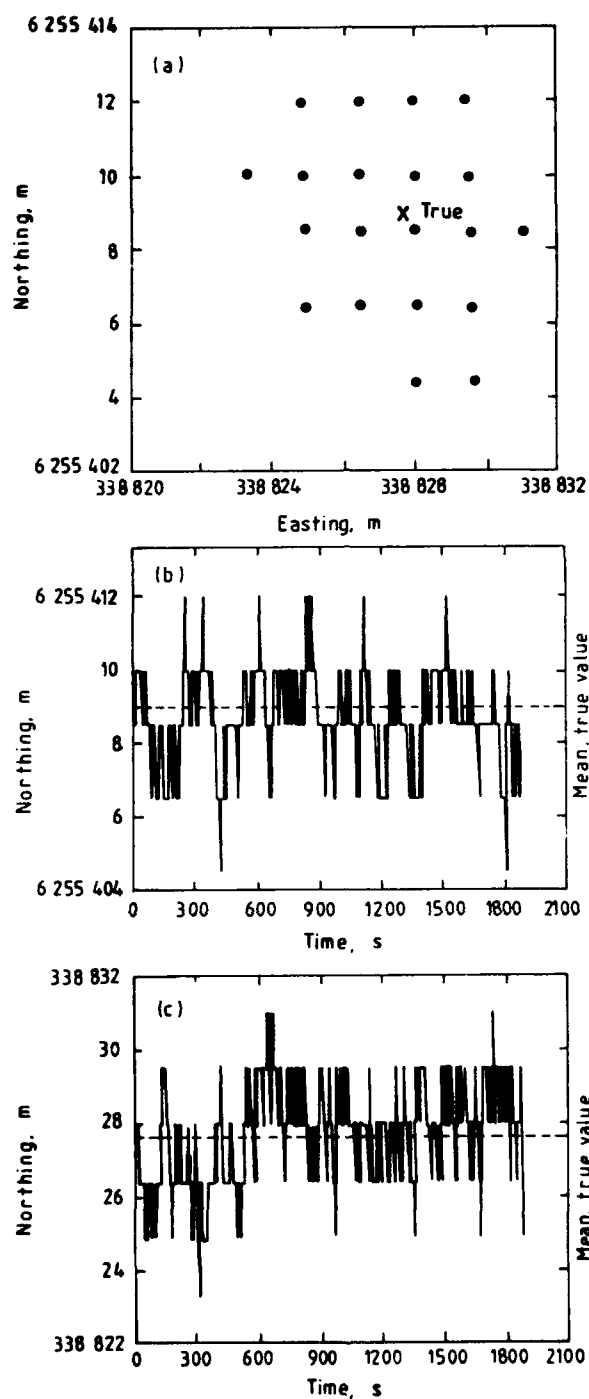
Figure 5: Static DGPS.(a), Differentially corrected position coordinates of Blocks E
datum, HMAS Penguin, 21 Nov. 1991, in AMG coordinates. The true surveyed position
is shown whereas the weighting of the individual data points spanning 32 minutes are not
shown. (b), Blocks E easting coordinate; the spread is 8 to 10 m whereas the difference
between the mean and surveyed value (338827.654 and 338827.679 respectively) is far
less. (c), Blocks E northing coordinate; the spread is 6 to 8 m whereas the difference
between the mean and surveyed value (6255408.706 and 6255408.814 respectively) is far
less.

This static DGPS experiment was repeated at a later date because no information was initially available in relation to the effect of satellite changes on positioning reliability. This time, the choice of satellites used by the GPS receivers changed three times at each receiver during the two hours of recording. The results are shown in Figure 6 which should be compared with Figure 5a. Interestingly, there was not an exact correspondence between tracking periods for particular satellites. The effect of satellite changes is observed as a transient increase in the HDOP which is displayed in Figure 7. On at least one occasion, there was considerable delay between an HDOP change at the reference station and the corresponding change at the remote receiver. This difference caused an increased error in the differentially corrected data which decreased as stable satellite tracking resumed. The observed delay can occur if a satellite at one site is temporarily hidden from view and an alternative satellite is tracked, leading to a different HDOP between reference and remote receivers.

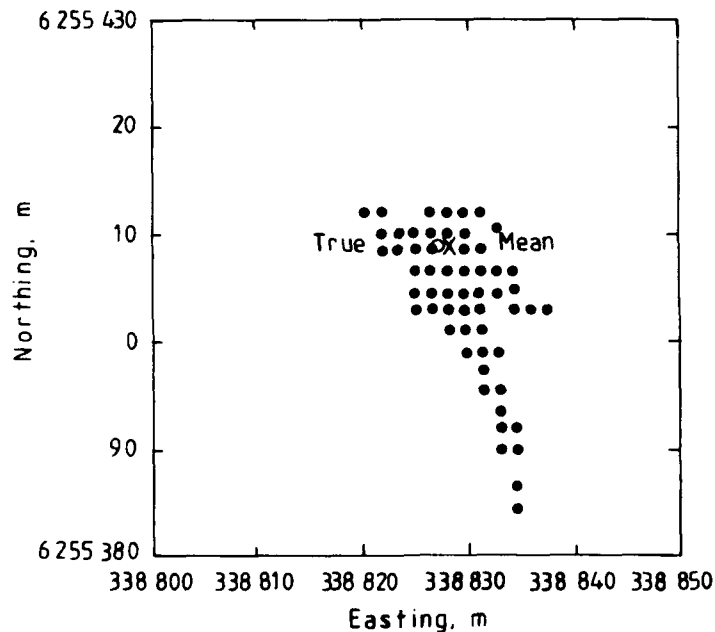*Figure 6:* Static DGPS coordinates of Blocks E datum, 13 Dec. 1991, compare with Figure 5a. Here, satellites used for GPS tracking were changing resulting in a greater spread of coordinates owing to inconsistencies between receivers. Data is shown covering the same time interval as Figure 5a. The DGPS mean easting/northing values averaged over 30 minutes and 3 hours are 338828.400/6255406.103 and 338828.538/6255409.148 respectively.
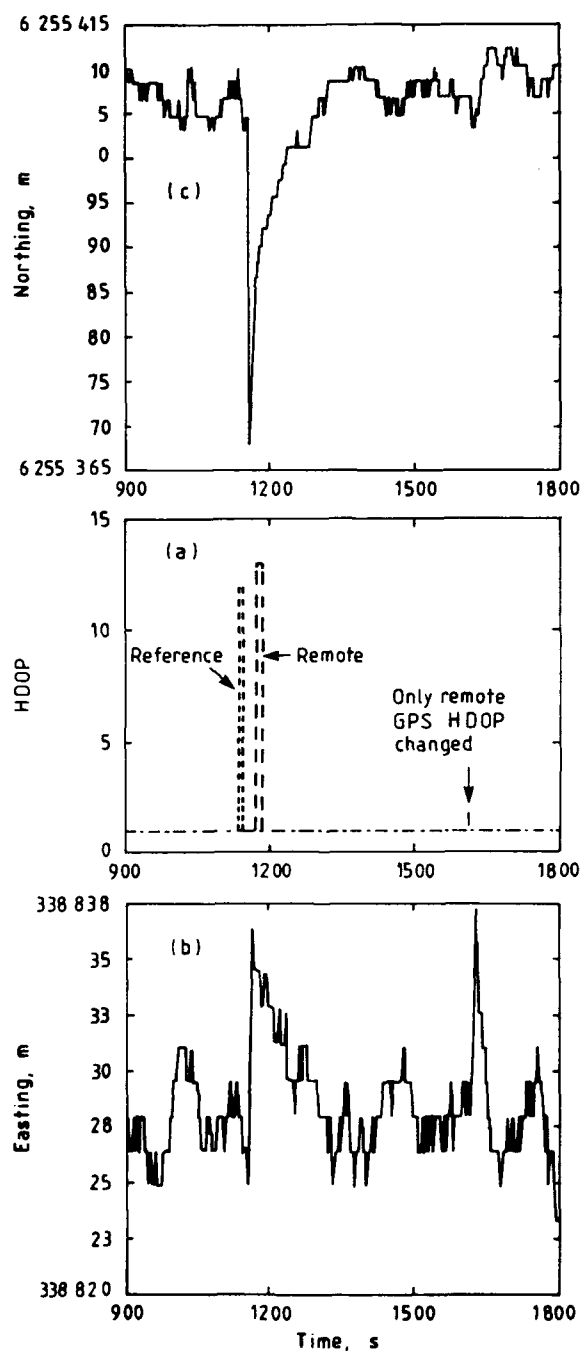
Figure 7: *(a) HDOP variations over a 15 minute interval at Pyrmont reference station and HMAS Penguin remote station, 13 Dec. 1991. (b), (c) : variations in easting and northing coordinates for HMAS Penguin datum (as shown in Figure 6) resulting from changes in HDOP factor.*

Generally, the satellite visibility is closely dependent on a combination of satellite geometry and the local environment of a receiver station. It is not always possible to determine the exact reason for the observed HDOP differences between stations. When satellite changes are occurring, data should be recorded for a longer time so that the contribution of non identical receiver errors to position uncertainty is clearly understood from the corresponding peaks in the corrected data, which may last up to a few minutes. For the data shown in Figure 6, the overall position error after averaging is about 3 m. By extending the recording period to three and a half hours, which includes more satellite changes, the accuracy is increased to about 1 m.

The previous results have relied upon the existence of a surveyed datum either at *HMAS Penguin* or at DSTO, Pyrmont. By contrast, a DGPS survey was undertaken prior to a conventional survey for establishing a datum. In this case the DGPS survey was carried out over a slightly longer baseline with the remote GPS receiver on a cliff top site at *HMAS Watson*. The location of this datum was required during an experiment which involved measuring the range to a moving off-shore vessel. In addition to the location being undetermined before the DGPS survey, the height of the cliff where the antenna was placed was known to only about 5 m accuracy. Thus the altitude parameter in the GPS receiver could have been in error by up to 10%, with unknown effects on the precision of the 2D position fix. The GPS data was recorded for about 10 minutes and no change of satellites occurred. The HDOP remained low for the duration of the survey. The coordinates of a point a few metres from the antenna position were later determined using conventional surveying techniques so that any uncertainty could be resolved.

The conventional survey result was found to be in close agreement with the GPS determined value. Since the position of the GPS antenna and the survey mark did not correspond exactly, the extent of agreement could not be accurately assessed. For this reason, the small uncertainty in the altitude parameter had an unknown effect. The easting,northing results for the mean DGPS and conventional surveys were 341082.2, 6254065.3 (height 56 ± 3 m) and 341086.5, 6254068.1 (height 51 m) respectively

A later survey at Chowder Bay, Sydney Harbour, highlighted the importance of the antenna height parameter. The baseline between Chowder Bay and Pyrmont was of a similar length to that in the *HMAS Watson* survey. Data was recorded for 10 minutes on two consecutive days under similar conditions of a steady HDOP of 1 with no satellite changes. The erroneous altitude parameter used on the first occasion, 56 m instead of 20 m, caused a significant difference. The corrected position fixes were spread over a noticeably larger area, but the offset between the mean positions for each set of data was greater than 20 m, see Figure 8. The results suggest that the antenna height should be reasonably well known beforehand if 2D position fixing is to be used for precise DGPS static solutions.
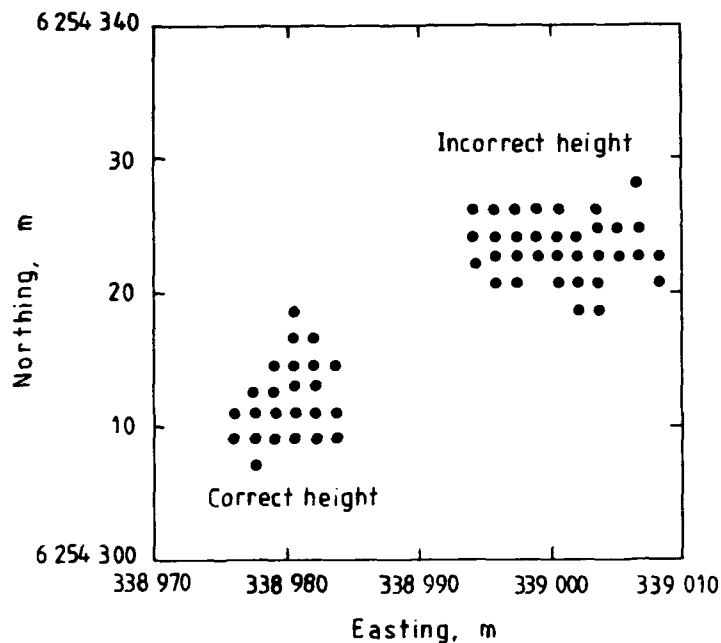
6 254 340

30

E

Northing,

20

Incorrect height

10

Correct height

6 254 300

338 970   338 980   338 990   339 000   339 010

Easting, m

Figure 8: *Effect of antenna height on AMG coordinates at Chowder Bay determined by DGPS. Separation of position fixes into two separate groups for correct and incorrect antenna heights.*

4.2 Marine Measurements

There are difficulties associated with using static GPS measurements of buoy positions to determine the location of datums resting on the seafloor. The adopted procedure, whilst executed as carefully as possible, nevertheless leads to a decrease in the positional accuracy of the DGPS method. The problems are best discussed by using an example where the positions, and relative position, of two sensor units (referred to as M and E) in about 18 m of sea water are required. A Navy clearance diving team was required to locate sensor M, and mark a deployment datum about 40 metres magnetic east for sensor E. Sensor M had been previously surveyed using GPS and laser tracking (14 August, 1992). Sensor E was surveyed similarly immediately after deployment (4 September) and both sensors were later surveyed together (9 September) when the results of the first two surveys indicated a misalignment of sensor M relative to sensor E.

The method of survey required a diver at the surface to swim alongside a marker buoy secured by a taut line to the underwater sensor to prevent drifting, and to hold either a GPS antenna or a reflector in a stationary position long enough to enable the geographical coordinates or range and bearing to be measured by the GPS receiver or laser tracker respectively. The results of these three surveys are shown in Figure 9. The position discrepancies reflect errors arising from a number of uncontrolled sources. These include the time delays required for the diver to exchange the antenna for the laser tracking reflector, as

well as relocating to the other sensor where applicable, and marker buoy movements influenced by sea state.

The relative positions of the E and M sensors based on the 9/9/92 measurements as shown in Figure 9, are considered to be the most accurate because both sensor positions were determined together, during very calm sea state conditions, and they agree with the intended deployment plan. These static DGPS trials and comparison with equivalent laser tracking position fixes give a good indication of the difficulties associated with such procedures as well as providing a check on the consistency of the data.

A more reliable method of obtaining a GPS position is to use the A-frame on the Navy workboat AWB 440 to lower the E sensor[4] to the seafloor and then to apply a lifting force. With the aerial mounted on the A-frame, the GPS reading is taken at the point of lift which is identified by the onset of strain on the cable drum. This method ensures that the sensor is located as vertical as possible below the GPS aerial.
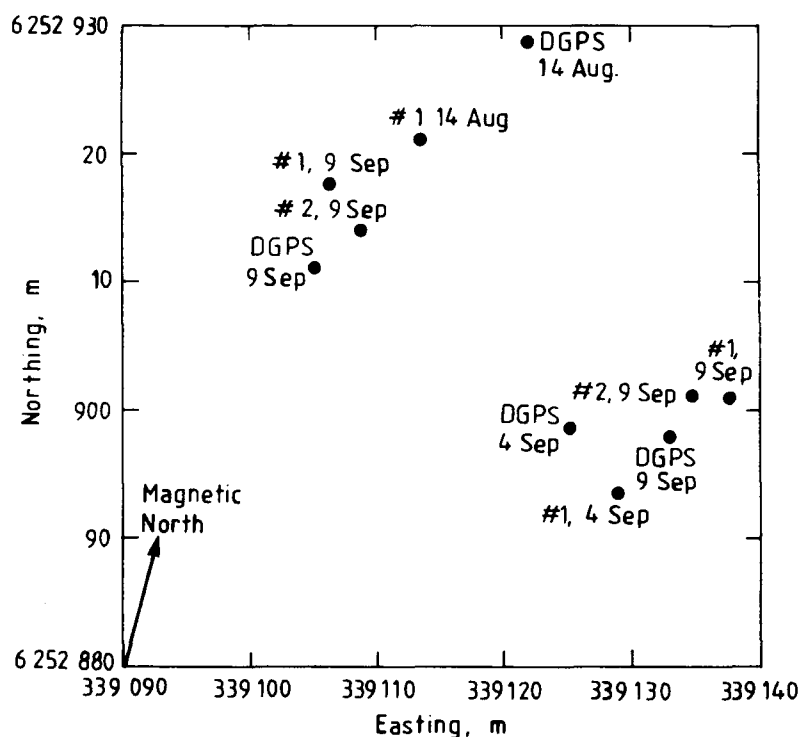

Figure 9: AMG coordinates of M and E sensors located on the seabed in about 18 metres sea depth, determined by laser tracking and DGPS techniques. #1 and #2 refer to the north and south laser tracker position fixes respectively.

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[4] The mass of the E sensors is 620 kg in air and 200 kg in water.

5. Kinematic DGPS

5.1 Introduction

Requirements for the development of a differential mode positioning system using GPS were governed by the nature of the experimental task being undertaken. The experiment involves measuring signals from a submerged dipole attached to a vessel steering along a predetermined course while the detection apparatus is situated on the seafloor, see Figure 10. The effect of various parameters on the detected signals is of major interest and determines the nature and location of the source-sensor experiment. Relevant variables that are subject to investigation include typically the sea bed composition as well as the range and direction of the source relative to the sensor. Consequently not only is the source-sensor geometry important, but also the ability to repeat the experiment at dissimilar locations enabling a comparison of results under different environmental parameters. To do so would require an easily transportable tracking system that could operate irrespective of location.
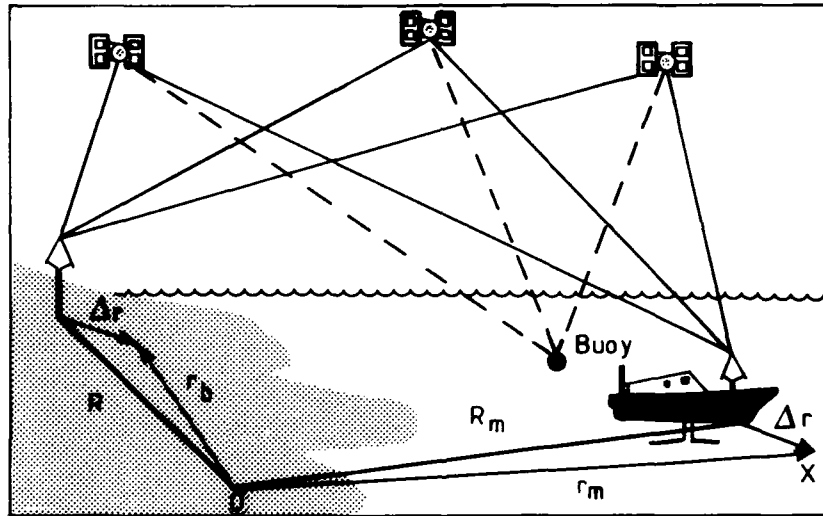
Figure 10: Kinematic differential GPS; the two receivers track identical satellites giving $r_b(t)$ and $r_m(t)$. The error in position $\Delta r(t)$ given at the reference station is subtracted from $r_m(t)$ to give the corrected position $R_m(t)$. R is the known position of the reference from a common origin at O and the buoy marks the location of the underwater sensors. The buoy position is also determined using differential GPS.

Before the DGPS system was in use, such experiments were performed at the Degaussing (DG) Range within Sydney Harbour [4] using the permanently installed laser tracking facility whereby boat movements were accurately monitored and recorded. When working to its full potential the laser tracking system is able to precisely measure boat position and direction anywhere in direct line of sight provided the vessel being tracked has special reflectors mounted at the bow and stern. The positional accuracy is superior to DGPS. The facility provides reliable vessel positioning data in a graphical hardcopy form. The proximity of the sensors to surveyed positions of underwater magnetometers (see Appendix and [4]), is given by assisting divers and the location is marked on each graph. In analysis of the results, the experimental geometry between source and sensor is simply determined by taking measurements off the appropriate graph.

Despite the success of the tracking system it does not allow complete freedom of choice in experimental conditions. Boat movements using this set-up are confined to a region of Sydney Harbour where the sea depth and seafloor type have limited variations. Furthermore, the speed, length and direction of boat manoeuvres are limited at the site owing to harbour operating restrictions and the fact that the laser track plots are available over a total of only 300 m about the DG range centre. Dipole transmission experiments require alternative sites to be tested, which in turn demands a transportable tracking system. Off-shore trials along the Manly coastline and Broken Bay region have been successfully completed using DGPS.

Results from static DGPS fixes in the previous section suggest that at any moment in time, a differentially corrected position fix may be about 5 m from the correct value under most conditions. Unlike static DGPS positioning, the situation involving a mobile antenna cannot be significantly improved by averaging fluctuations. Smoothing algorithms can be implemented but the overall increase in accuracy is in most cases small.

5.2 Laser Tracking Versus DGPS

The accuracy of the DGPS track data was checked by comparison with laser tracking. The ensuing comparison required the development of some additional software to make a transformation from the GPS datum to either one of two unique local grid systems used at the DG Range, see Appendix. Since the data from the laser trackers were more conveniently obtained as a hardcopy plot using the local grid system, the DGPS results were converted to the same coordinate system to enable a direct comparison.

Each of the two local coordinate systems, one for the Deep Range and one for the Shallow Range, is aligned with its respective range axis. In both cases the range axis lies close to magnetic north at the time of survey in 1983, see Appendix. The origins of the coordinate systems are the number one magnetometer in the shallow array, and the number four magnetometer in the deep array[5]. When converting to the local systems from the AMG easting/northing coordinates routinely determined from the DGPS data, the local convergence must also be taken into account. This is the angular disagreement between the AMG grid north and the corresponding geographical true north given by the GPS receiver.

---

[5] The outer three magnetometers in the deep array are not usually included on the laser tracking grid, however in the case of the GPS method, the grid is extended in increments of magnetometer displacements to include the uncorrected GPS track.

Coordinates for the magnetometers and the bearings of the DG Range axes are found in the Appendix.

5.2.1 Navy Workboat Trials

The initial kinematic comparative study between DGPS and laser tracking was undertaken with a relatively small boat (AWB 440) with reflectors fitted bow and stern, separated by a baseline of about 12 m. The laser tracking exercise was difficult because of the small boat momentum which resulted in sharp angular motions (skew). This motion often prevented the laser tracking software from allowing a successful completion of a ranging. Despite these difficulties, several measurements were completed and the overall close agreement between the DGPS tracks and those obtained from the laser trackers was very encouraging. Two examples are shown in Figures 11 and 12 representing measurements recorded over the deep and shallow ranges respectively. The GPS data, after differential correction, appears to deviate from the laser tracker data by consistently less than 5 m. This follows closely the instantaneous error expected from the study of static DGPS position fixes above. Of particular interest is the difference between the DGPS tracks and the uncorrected GPS data. Prior to differential correction, the GPS data is found to vary by up to 60 m from the true position given by the laser trackers. The degree of difference varies significantly with time and satellite conditions but by using DGPS the effect of this inconsistency is reduced by an order of magnitude. The extent of correction between the GPS and DGPS data, as determined by the reference station at Pyrmont, is clearly visible. For a kinematic position measurement over several hundred metres, a positioning error of only a few metres is expected when DGPS is implemented.

5.2.2 Submarine Trials

In order to obtain a more complete verification of the DGPS accuracy during sea trials, a further study was undertaken in which the positions determined by DGPS were compared against the laser tracking solutions for the case of reflectors fitted bow and stern of a 90 m long submarine. This trial offered several advantages over the AWB 440 trial. The reflector baseline separation of 75 m combined with the considerably larger momentum of the vessel ensured a steady track with a very high rate of successful laser tracker rangings. In addition, the total of 44 rangings, each tracked over a length of 700 m, provided a far greater number of experimental data records than had ever been obtained previously. The large variety of satellite geometries occurring during the two day trial also provided the opportunity for examining any disagreement with laser tracker positions due to varying reference and remote station HDOP factors. For the purpose of this trial only, the satellites used in determining the reference GPS position were identified by video recording the receiver display, whilst the satellites used by the remote receiver were recorded manually for each ranging.
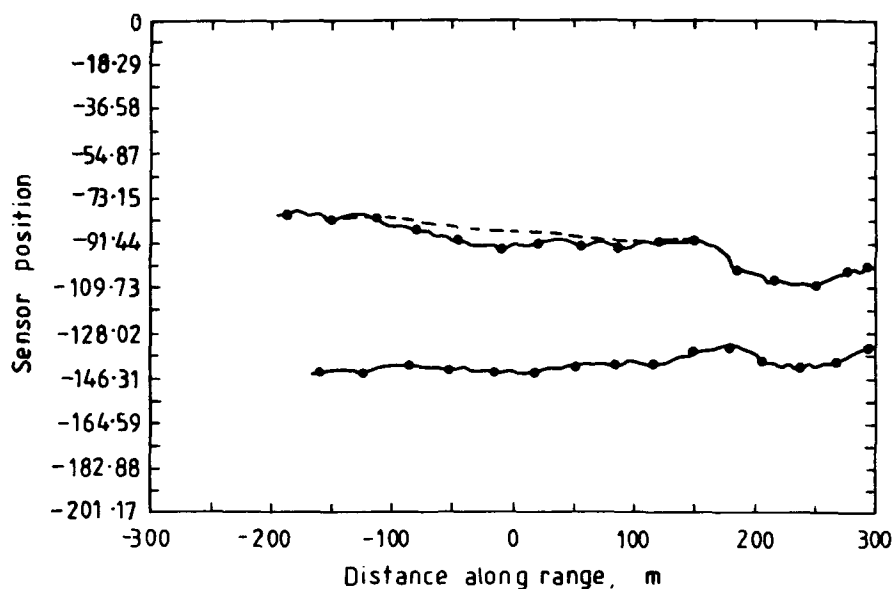
Figure 11: *Kinematic DGPS tracking on the deep range, Shark Point; corrected and uncorrected tracks are compared with laser tracking (dashed line). Corresponding 10 second intervals are marked. The corrected GPS track is the one coinciding with the laser track.*

Figure 12: *Kinematic DGPS tracking on the shallow range, Shark Point; corrected and uncorrected tracks are compared with laser tracking (dashed line). Corresponding 10 second intervals are marked. The corrected GPS track is the one coinciding with the laser track.*
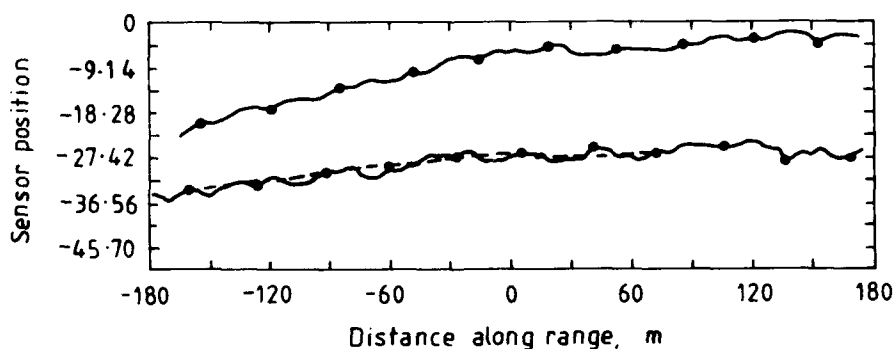
During the trials period 44 tracks were recorded and of these one completely failed as a result of the remote GPS receiver being unable to lock onto the 3 satellites required for a 2D solution. Two other runs included small sections where similar mistracking occurred and data could not be recorded, probably as a result of temporary obstructions of the submarine GPS antenna which was mounted about 1 m above the central tower section (fin). A few failures were registered with the laser trackers and some runs indicated that only one tracker was correctly locked on to its target. Compared to the total number of rangings, the number of runs with bad agreement between DGPS and laser tracks due to incorrect data acquisition is small. The only significantly bad runs apart from those already mentioned are #6, and #34 which contained errors of about 30 m for most of the run. A total of only 9 DGPS tracks had deviations in excess of 7 m. These errors, which in most cases did not exceed 15 m, were a result of satellite/HDOP discrepancies between the two receivers.

Results indicate that this situation may not necessarily lead to large track perturbations. In fact, many of the runs involved inequivalent satellite/HDOP changes at the receivers yet did not display track deviations greater than 7 m, which is tolerable considering the expected instantaneous errors in the static DGPS case. For the 35 runs showing good agreement between laser tracks and DGPS, the differences were usually about 2 to 5 m. Interestingly, only 19 of these runs were found to have exact correspondence between the satellites tracked by the two receivers. For some of the runs with satellite differences, the HDOP remained constant, indicating that at the time there was a multiplicity of low HDOP satellite configurations available. At other times, satellite changes at either the reference or remote receiver were accompanied by a rise in HDOP. In these cases the changes were initiated by active satellites moving out of view or into a poor geometrical position, with no alternative optimum HDOP configurations becoming available for some time.

A summary is shown in Table 1. The laser track is assumed to be the correct position unless otherwise specified. 'Close agreement' between tracks includes differences of up to about 7 m. Amongst the tracks with greater deviations than this, most include only a few seconds of erroneous positions which rarely exceed 15 m. Runs #23 and #28 show close track agreement but contain breaks due to mistracking. For the runs indicated as such, no satellite information was recorded.

Examples of track agreement representative of the variations described in Table 1 and above are shown in the following Figures. Unlike the AWB440 trials, the tracks are considerably straighter as expected, and an improved solution for linear GPS tracks would obtain by least squares fitting. An example of a typical run with small deviations from the laser track is shown in Figure 13 (run #8), the inset is an expanded portion showing the locations (#1, #2) of the M and E sensors, see Figure 9. The maximum deviation is 3 m. An example of two runs with larger deviations is shown in Figure 14. At the beginning of run #6 (Fig. 14a), large errors of about 10 m arise from satellite changes which result in different HDOP factors at the reference and remote receivers. The rest of the run shows small deviations once both GPS receivers are tracking the same satellites. Run #38 (Fig. 14b) shows the effect of intermittent satellite switching and consequent HDOP changes. In some cases, as shown in Figure 14c, minimal deviations were found when there was a single satellite discrepancy throughout the complete run.
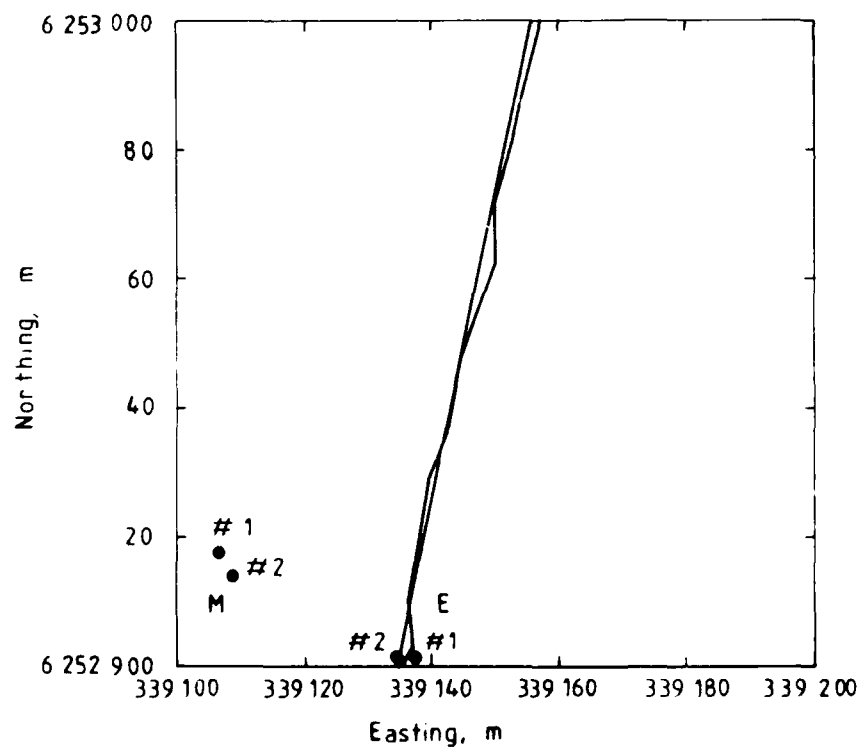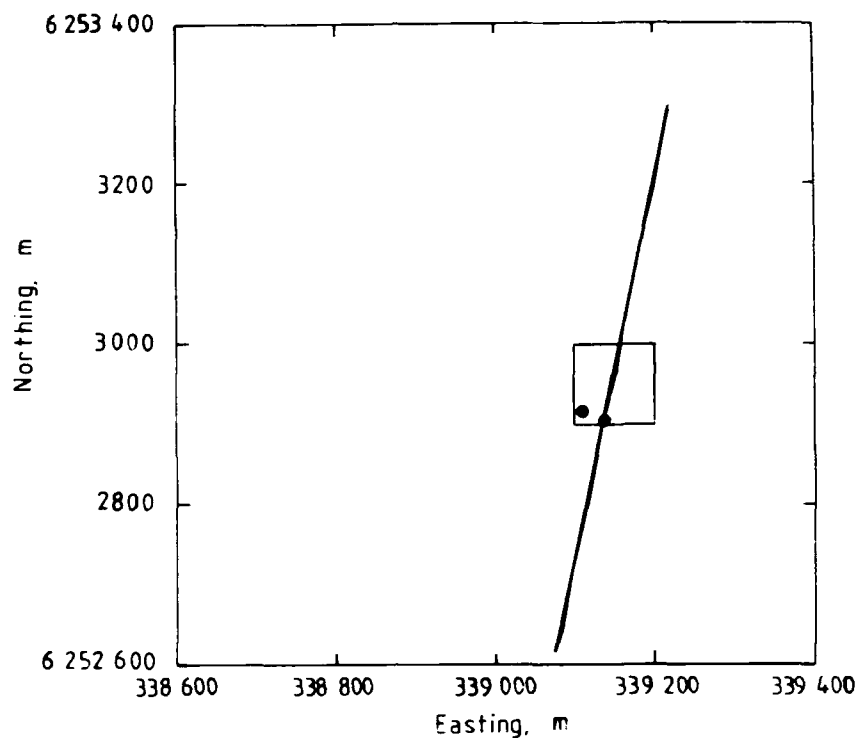
Figure 13: Kinematic DGPS tracking of run #8 (see Table 1) where HDOP did not differ or change, compared with laser tracking. The square region containing the underwater sensors is expanded showing the M and E sensor locations determined by #1 and #2 laser trackers, see Figure 9.
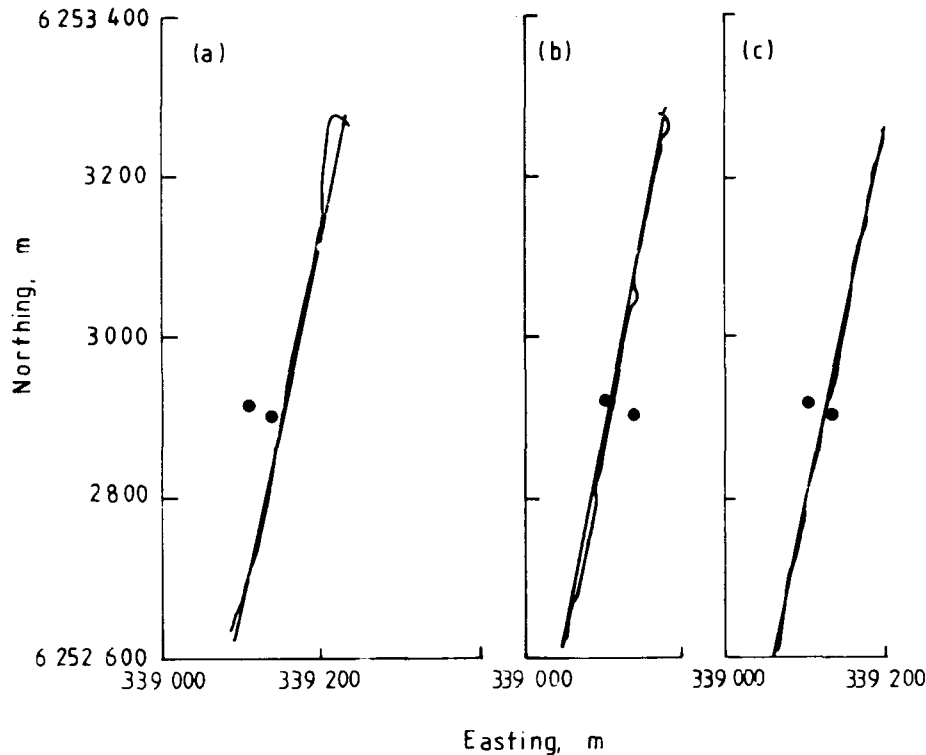
6 253 400

(a)   (b)   (c)

3 2 0 0

Northing, m

3 0 0 0

2 8 0 0

6 252 600
339 000   339 200   339 000   339 000   339 200

Easting, m

Figure 14: *Kinematic DGPS tracking errors, see Table 1, compared with laser tracking. (a), run #6 has a large error at the start caused by satellite changes and differences which caused different HDOP factors at each receiver. (b), run #38 shows significant errors arising from switching of satellites in two regions. (c), run #21 shows good agreement even though one different satellite between the two GPS receivers is being tracked throughout the entire run.*

Table 1: *Variations between GPS and laser tracking positioning**

	Tracks with close agreement between GPS and laser tracking deviation < 7 m	Tracks with deviations > 7 m
Satellite and / or HDOP changed or differed between remote and reference GPS receivers	[3],5,16,(21),(22),24,31,32, (36),(40),45,46,(47)	6,[(7)],[10],14,(23),(26), [(28)],34,38
No satellite changes and no HDOP differences	[1],[2],[4],8,9,11,12,13, 15,17,20,27,25,29,30,33, 35,37,39,41,44.48	nil

*   Runs #18, #19, #42, #43 were only recorded for GPS, laser tracking restricted to centre of shallow range, see Section A.2.

[#]   Status of satellite changes not known.

(#)   HDOP not affected by satellite changes.

{#}   Segment of GPS track missing arising from failure of submarine GPS receiver locking onto satellites.

6. Submarine Tracking

A recent requirement is tne ability to accurately track submarine movements in proximity to sensors placed on the seafloor. Even if GPS is fitted to the submarine as will almost certainly be the case in the near future, unless operation is in differential mode, the GPS unit used at the remote site on the submarine should be identical to that used at the Pyrmont reference site so that consistent subtraction of GPS receiver instrument errors apply during the differential correction.

Whilst sea water skin depth attenuation limits any GPS application to above water reception, accurate positioning using GPS is still available for a submarine operating at periscope depth. Two alternatives are possible. The first is to use a separate GPS antenna contained in an underwater casing mounted to an appropriate point on the fin or tower and to use a hull gland to allow the signal to be passed through the hull to the receiver. This method is most undesirable. The second method which proved very successful was to remove the preamplifier unit which is normally mounted in the weather-proof GPS antenna casing and interface it to the UHF mast of the submarine. The antenna preamplifier is linked to the receiver which is thus convinced that it is receiving the GPS transmissions from its own original aerial. The submarine gains GPS navigational capability at the expense of minimal internal modifications for the cost of a relatively cheap GPS receiver. No external modifications are required.

7. Conclusion

The relatively recent technique of DGPS has been applied in the form of post processing the recorded GPS data from two geographically separated receivers. This methodology was applied to terrestrial static examples, firstly to demonstrate the accuracy and reliability of the technique, and secondly to gauge the minimum expected errors for kinematic applications. In the former case, the accuracy was limited to the resolution of the receiver instrument, which is about 1.8 m, for 10 minutes of data at a 2 second sampling rate. The static DGPS method was also used to determine the position coordinates of fixed sensor locations placed on the seafloor. The difficulties with marine static DGPS applications arise from fluctuating buoy movements away from the vertical line from seafloor to surface. The consistency between repeated measurements of the same seafloor datum using laser tracking and GPS methods was generally found to be in good agreement considering time delays between measurements and differing weather conditions. The sea state conditions and underwater currents influence the positioning errors more than the inherent errors associated with the DGPS method as applied in this study.

Kinematic measurements have been successfully implemented to enable the coordinate track of various vessels to be accurately determined to within +/- 5 m. Kinematic DGPS records were compared to simultaneously obtained laser tracking positions which are more accurate, in order to test the accuracy under the usual sea trials operating conditions of the vessel, i.e. speed and length of track. Two vessels were used for these trials, a 12 m long workboat which is normally used for sea trials involving the use of an underwater calibrated dipole source [5],

and a 90 m long submarine. The latter provided a less erratic track and measurements were undertaken over the longer period of two days thereby producing more data and giving the opportunity to examine the DGPS errors over a greater variety of satellite constellation geometries.

Kinematic DGPS measurements have enabled the time varying position of a vessel relative to a fixed sensor to be measured at several geographical sites covering the Broken Bay region, open sea off the Manly coastline and Sydney heads and within Sydney Harbour. An overall 8 m error could be associated with such relative distance measurements based on individual 5 m DGPS errors. Depending on the water depth and sea state, this error may increase slightly because of additional uncertainties introduced by fluctuating buoy movements marking the seabed sensor location.

The GPS receiver unit has been interfaced to the UHF submarine antenna mast to enable GPS navigational accuracy for both fully surfaced and periscope depth operating states.

8. Acknowledgements

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Appendix:

Conversion of Degaussing Range Coordinates to Geographical Coordinates

The position coordinates obtained from the DG range need to be transformed to the commonly used geographical coordinates, latitude and longitude, in Australian Geodetic Datum 1966 (AGD66) coordinates[6]. This is useful for determining any DG Range locations or navigating to waypoints on the range using GPS reception, for example, magnetometer locations for normal ship ranging and for providing datum points for positioning additional seabed sensors. The other important application is the conversion of laser tracking data. The geographical coordinates then need to be converted to Australian Mapping Grid (AMG) coordinates [3] to determine correct distances. All grid coordinates are in metres.

A.1 Magnetometer Array Coordinates

The coordinates of the deep and shallow linear array of magnetometers are given in two unique local coordinate systems (DG-d, DG-s respectively) defined by the Australian Survey Office, with the origin of each system located at the centre of each array. The only other information is the coordinates of the two laser tracking pedestal mounts (north, south) provided in both the local coordinate systems and Integrated Survey Grid (ISG) coordinates[7]. Thus it is possible to transform all local coordinates to ISG coordinates by a simple transformation. These coordinates can then be transformed to AGD66 coordinates. The coordinates of the north and south tracker datums for the shallow range are (324402.381 E, 1252837.110 N)$_{ISG}$, (4.015, -154.933)$_{DG-s}$ and (324402.391 E, 1252834.586 N)$_{ISG}$, (1.556, -155.482)$_{DG-s}$) respectively. The deep range coordinates for north and south tracker datums are (324402.381 E, 1252837.110 N)$_{ISG}$, (5.675, -375.619)$_{DG-d}$ and (324402.391 E, 1252834.586 N)$_{ISG}$, (3.215, -376.167)$_{DG-d}$) respectively.

The transformation, see Figure A1, is given by

$$x = x' \cos\alpha - y' \sin\alpha + x_o$$

$$y = x' \sin\alpha + y' \cos\alpha + y_o$$

---

[6] AGD66 coordinates have been used for GPS position fixing as a matter of convenience because the most comprehensive range of available Navy charts use the same reference coordinates. New charts and all future ones will be replaced by the AGD84 coordinate datum. The FURUNO GP-500 allows a choice of either AGD66 or AGD84 geodetic coordinates in addition to WGS84/72.

[7] ISG and AMG coordinate systems both express the position in metres in easting (E) and northing (N) coordinates, however different datums are used. The following parameters are required for conversion between the ISG (AMG) coordinates and AGD66 latitude/longitude geographical coordinates [3]. Spheroid selection: Australian (Australian), projection: transverse mercator (transverse mercator), grid: other (UTM, southern hemisphere), false easting :300,000 (500,000), false northing: 5,000,000 (10,000,000), central meridian: 151 deg, 0 min, 0 sec , east (153 deg, 0 min, 0 sec , east), scale factor on central meridian: 0.99994 (0.9996) and latitude of origin: 0 deg, 0 min, 0 sec, south (not required as specified under grid choice).

---

where x',y' are local coordinates unique to the deep and shallow ranges and x,y are ISG coordinates. The above laser tracker datum coordinates are substituted into the expression to solve for the ISG origin coordinates of the two ranges, x_o, y_o. The shallow range origin determined from the north and south tracker datum is 324250.381(E), 1252866.370(N) and 324250.173(E), 1252866.365(N) respectively. The origin for the deep range is 324034.262 (E), 1252912.012(N) and 324034.264(E), 1252912.008(N) respectively for north and south tracker datums. The agreement between origins determined from north and south datums for both deep and shallow ranges is excellent and the average value for x_o, y_o is used in the above transformation for converting the local magnetometer coordinates to ISG and AMG coordinates. The results in AGD66 and AMG coordinates are plotted in Figure A2.

$$\alpha = 77° \quad 44' \quad 42'' \text{ shallow}$$
$$\alpha = 78° \quad 07' \quad 27'' \text{ deep}$$
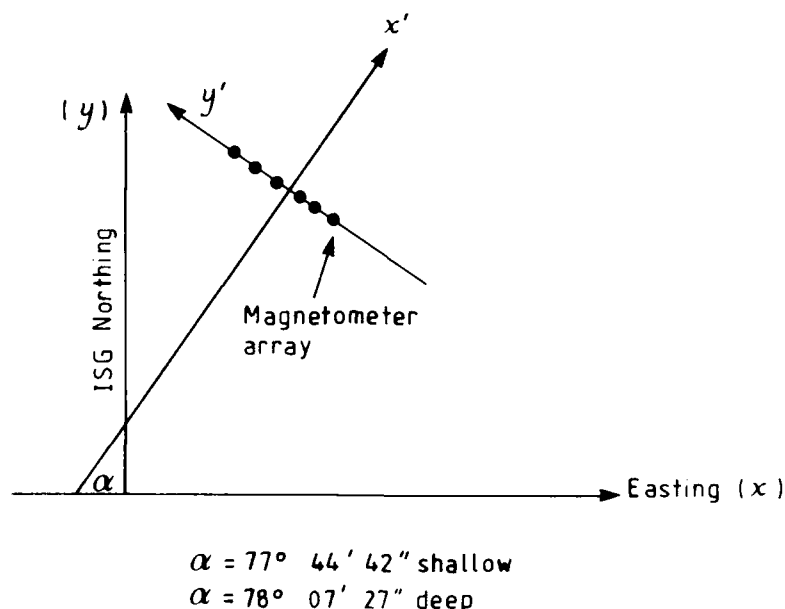
Figure A1: *ISG (x, y) and local deep and shallow range (x', y') coordinate systems.*

A.2 Laser Tracking Coordinates

Laser tracking coordinates are usually displayed on a grid aligned in such a manner that the magnetometer linear array forms one axis using a line of best fit. The orthogonal axis refers to the range axis which has a different bearing for the shallow and deep ranges, see Figure A3a. This system is used to identify the track as a vessel is being ranged over the magnetometer array. In order to compare GPS data to tracking coordinates, the GPS data is first transformed to AMG coordinates which in turn are then transformed to the rotated coordinate system used for the deep and shallow range magnetometer arrays. Thus with reference to Figure A3b,

$$x = R\cos(\phi - \phi_o)$$
$$y = R\sin(\phi - \phi_o)$$

31

where

$$R^2 = (\Delta E)^2 + (\Delta N)^2$$
$$\Delta E = x_{coord} - x_o$$
$$\Delta N = y_{coord} - y_o$$

and x_{coord}, y_{coord} and x_o, y_o are the positions of the vessel and magnetometer array origin respectively in AMG coordinates. The local convergence for the AMG (ISG) northing is 0.967 (-0.147) degrees [6] and this factor which measures the difference between true north (meridian of longitude) and the AMG (ISG) northing direction needs to be included when determining the ϕ_o angle ($\equiv \phi^s_o$, ϕ^d_o for shallow and deep ranges respectively) , see Figure A3a. This method was used to compare GPS accuracy against laser tracking, for example, as shown in Figures 12 and 13.

The display of laser tracking positions on the magnetometer array coordinate system as described above, is too restrictive in most cases as it does not allow the display of any tracking data within regions removed by ± 150 m from the magnetometer arrays. In order to compare GPS and laser tracking position values and relative distances, the range and bearing of the laser tracking output is transformed to AMG coordinates by reversing the procedure outlined above, see Figure A3b. In this case however, the range axis bearing (shallow/deep bearing axis in Figure A3b) is replaced by the bearing of magnetic north, see Figure A3a, because the bearings of the raw laser tracker coordinates refer to this axis.
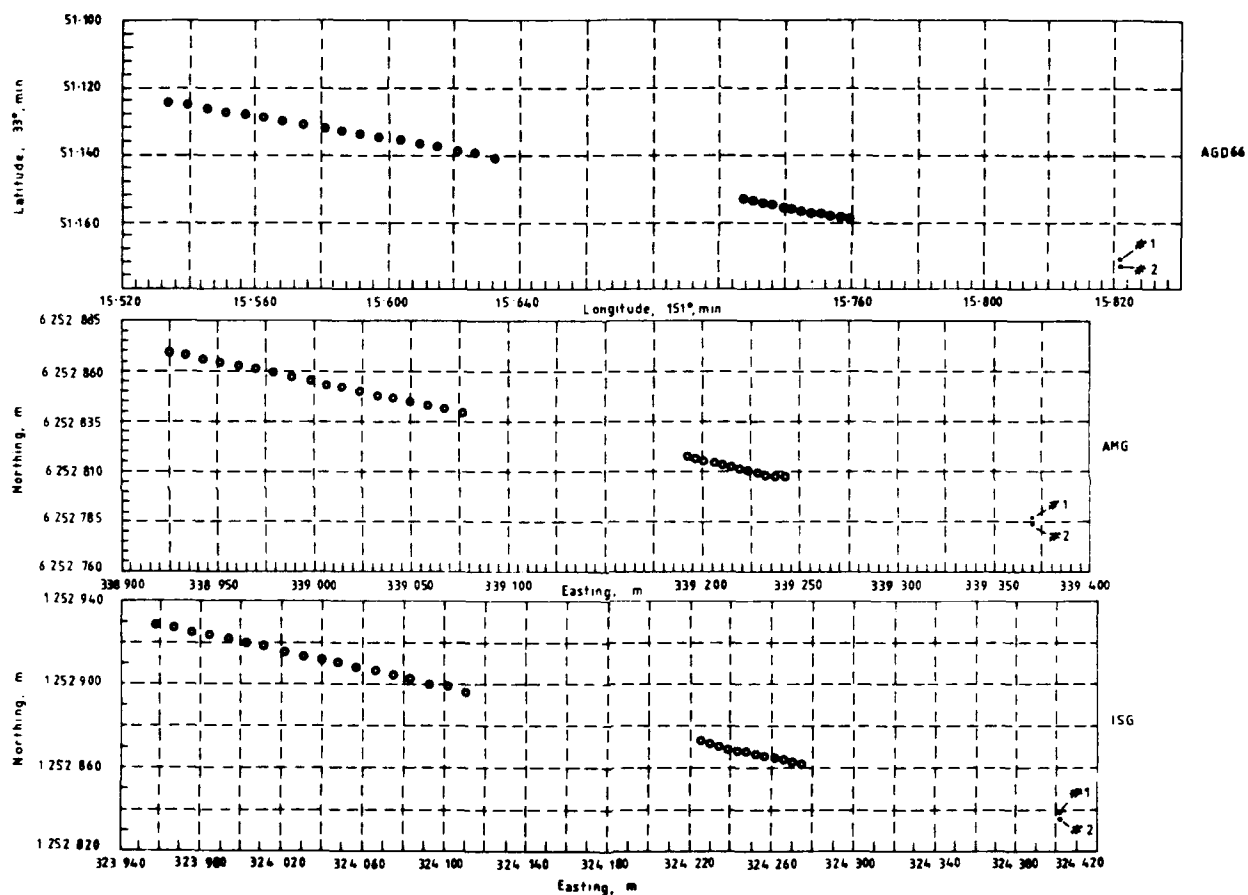
Figure A2: *Deep and shallow range magnetometer locations in geographical (AGD66), AMG and ISG coordinate systems including the #1 and #2 laser tracking positions.*

True

ISG

AMG $58' 2 \cdot 8'' = 0 \cdot 967°$

φ_c

Magnetic North
12° 22' (Feb 1983)
relative to ISG

Deep bearing

Shallow bearing

φ_0^d

φ_0^s

$\beta^s = 6' 42'' = 0 \cdot 112°$

$\beta^d = 29' 27'' = 0 \cdot 491°$

$8' 48' \cdot 8''$
$0 \cdot 147°$

Deep; line of best fit : 269° 30' 33"

Shallow; line of best fit : 269° 53' 18"

$$\varphi_0^s = 12° 22' - \varphi_c - \beta^s = 11° 8' 26 \cdot 4'' \ (11 \cdot 1407°)$$

$$\varphi_0^d = 12° 22' - \varphi_c - \beta^d = 10° 45' 41 \cdot 4'' \ (10 \cdot 7615°)$$

Northing
AMG

Shallow/deep bearing

y

ΔE

x coord, y coord

x

R

ΔN

$\varphi_0^{s,d}$

φ

Easting (AMG)

$x_o \, y_o$
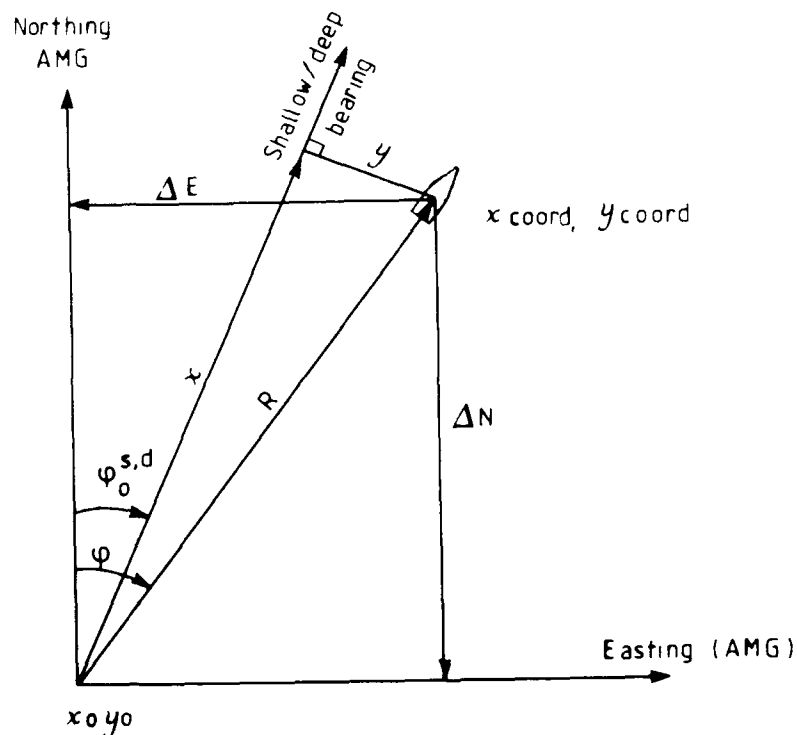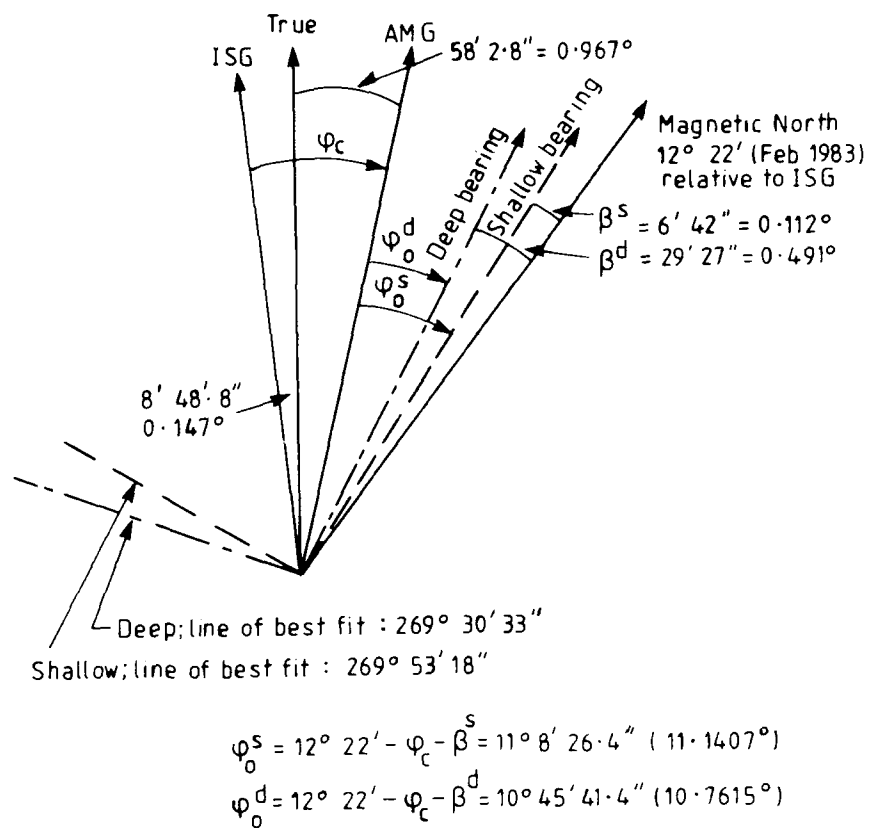
Figure A3a, b: *Laser tracking, ISG and AMG coordinate systems and definitions of angles φ_c, φ_o, β. Superscript "s" and "d" refer to shallow and deep ranges respectively.*

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TITLE

The determination of static and time varying dipole source - sensor geometry during sea trials using differential global positioning system

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ABSTRACT

Global positioning system (GPS) navigational equipment is used in differential mode to determine the time varying geometry of a boat attached to a submerged dipole source and a sensor positioned on the seafloor which is marked by a surface buoy. The requirement is to track the position of the source relative to the sensor on the seabed in sea depths less than 40 metres in the vicinity of Sydney Harbour. A differential GPS (DGPS) system is formed from two or three low cost navigational units, one of which is located at a surveyed reference site and the other is located onboard the vessel. A third unit may be temporarily located at the sea surface above the sensor positioned on the seafloor. The differential system relies on software developed to apply the GPS correction obtained from the reference station to the remote stations after the geographical coordinates have been recorded. Static DGPS measurements using a 7 km baseline between remote and reference datums gave a position accuracy limited by the resolution of the GPS receiver. As a test for kinematic DGPS, the positional accuracy of the moving vessel was checked against the position coordinates derived from the laser tracking facility of the Shark Point Degaussing Range, Sydney Harbour. The agreement was usually found to be better than about 5 m, typically ± 2 m. DGPS also enabled accurate submarine tracking at periscope depth by interfacing the submarine UHF antenna to the GPS receiver. A discussion of operational issues in the use of DGPS is also included.

The Determination of Static and Time Varying Dipole Source - Sensor Geometry During Sea Trials Using Differential Global Positioning System

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